Double Extensive Air Shower Induced by Ultra-High Energy Cosmic Tau-Neutrino

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We investigate the possibility of detecting ultra-high energy cosmic tau-neutrinos by means of a process involving a double extensive air shower, the so-called Double-Bang Phenomenon. In this process a primary tau-neutrino interacts with an atmospheric quark creating a first hadronic shower and a tau-lepton, which subsequently decays creating a second cascade. The number of these events strongly depends on the flux of tau-neutrinos arriving at the Earth's atmosphere and can be used to test some theoretical models related to the production of ultra-high energy tau-neutrinos. We estimate the potential of the fluorescence detector of the Pierre Auger Observatory to observe Double-Bang events. We conclude that for tau-neutrinos with energies ranging from $O(0.1)$ EeV to $O(10)$ EeV the number of detected events vary from hundreds in a year to only few events in hundreds of years.

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I. INTRODUCTION

It is believed that ultra-high energy cosmic neutrinos may play an important role to explain the origin of cosmic rays with energies beyond the GZK limit of few times 10^{19} eV [1, 2], once that neutrinos hardly interact with cosmic microwave background or intergalactic magnetic fields, keeping therefore its original energy and direction of propagation. Even if they have masses or magnetic moments, or travel distances of the order of the visible universe, those characteristics do not change very much. Possible sources of these ultra-high energy neutrinos, like Active Galactic Nuclei and Gamma Ray Bursts, are typically located at thousands of Mpc [3, 4]. Considering that neutrinos come from pions produced via the process $\gamma + p \rightarrow N + \pi$ [4], that there is an additional ν_e flux due to escaping neutrons and that about 10% of the neutrino flux is due to proton-proton (pp) interactions, the proportionality of different neutrino flavors result: $\nu_e : \nu_\mu : \nu_\tau = 0.6 : 1.0 :< 0.01$ [5]. Nevertheless, observations of solar [6] and atmospheric [7] neutrinos present compelling evidence of neutrino flavor oscillations. Such oscillations have been independently confirmed by terrestrial experiments. KamLAND [8] observed $\bar{\nu}_e$ disappearance confirming (assuming CPT invariance) what has been seen in solar neutrino detections and K2K [9, 10] observed $\nu_\mu/\bar{\nu}_\mu$ conversion compatible with what has been detected in atmospheric neutrino observations.

In order to understand these experimental results by means of neutrino oscillations, two scales of mass squared differences and large mixing angles have to be invoked. For solar and KamLAND observations, $\Delta m^2_\odot \sim 7 \times 10^{-5}$ eV^2 and $\sin^2 2\theta_\odot \sim 0.8$. And for atmospheric neutrino and K2K, $|\Delta m^2_{atm}| \sim 3 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{atm} \sim 1$. Moreover LSND experiment [11] may have observed $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transition which can be also explained by neutrino oscillations with a large mass scale, $|\Delta m^2_{LSND}| \sim (0.5 - 2.0)$ eV^2. Such results will soon be checked by MiniBooNE [12]. These scales require four neutrino oscillation framework (or three, if LSND results will not be confirmed by MiniBooNE experiment) which imply, for ultra-high energies of the order 1 EeV or higher, oscillation lengths much smaller than typical distances from the sources of ultra-high energy neutrinos. Consequently when neutrino flavor oscillations are taken into consideration the flavor proportion will be modified to $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$. Therefore one expects a considerable number of tau-neutrinos arriving at the Earth.

In this paper we investigate the possibility of detecting ultra-high energy cosmic tau-neutrinos by means of a process in which a double Extensive Air Shower (EAS) is identified, the so-called Double-Bang (DB) Phenomenon. In that kind of event a tau-neutrino interact with a quark via charged current creating one cascade of hadronic particles and a lepton tau which subsequently decays producing a second cascade. DB Phenomenon was first proposed for detectors where the neutrino energy should be around 1 PeV [5]. It does not happen with neutrinos different from tau. The electron generated by an electron-neutrino immediately interacts after being created and the muon generated by a muon-neutrino, on the other hand, travel a much longer distance than the size of the detector before interacting or even decaying. So we do not have DB events from them.

In order to identify a DB Phenomenon we have to look for two Extensive Air Showers (EAS) in the same direction of propagation inside the field of view (f.o.v.) of the detector, i.e., in the physical space around the detector in which an event can be triggered.

In the Pierre Auger Observatory [13], a hybrid detection technique will be used to make a detailed study of cosmic rays at energies mainly around 10 EeV and beyond. The two techniques consist of an array of de-

tectors spread on the ground (the ground array detector also called surface detector) and an optical detector used to probe longitudinal development of EAS by recording the fluorescence light emitted by the excited nitrogen molecules of the Earth's atmosphere. It has been shown that the Auger Observatory can detect atmospheric near-horizontal air showers generated by neutrinos with the surface detector [14, 15, 16, 17, 18, 19]. We concentrate here on a different approach to study the possibility of detecting events induced by ultra-high energy tau-neutrinos, the DB events, using the fluorescence detector of that observatory.

We conclude that the features of the Pierre Auger Fluorescence Detector favor the observation of DB events with tau-neutrino energies varying from $O(0.1$ EeV$)$ to $O(10$ EeV$)$, despite the low efficiency of the fluorescence detector at energies smaller than 1 EeV. We estimate the number of DB events observed in the fluorescence detector varying from hundreds in a year to few events in hundreds of years depending mainly on the primary tau-neutrino flux.

This paper is organized in the following way: Section II has a brief introduction to the DB Phenomenon. Section II A shows some results of the DB events simulated and Section II B describe how we calculate the number of events in the Pierre Auger Fluorescence Detector. Section III has the number of events calculated for different models of ultra-high energy neutrino flux and discuss how could we take some physical information from that. The conclusions are in Section IV, in which we discuss also the background events.

II. THE ULTRA-HIGH ENERGY DOUBLE-BANG AND THE AUGER OBSERVATORY

Studying the characteristics of the fluorescence detector, such as its efficiency and f.o.v. and the characteristics of the DB events generated by ultra-high energy tau-neutrinos, one can estimate the rate of that kind of event expected in the Auger Observatory.

Fig. 1 shows a schematic view of an ultra-high energy DB with the detector position and the time integrated development of the two showers, one created by the high-energy tau-neutrino interacting with a nucleon in the atmosphere and the other created by the decay of the tau generated in the first interaction of the tau-neutrino. The f.o.v. of the fluorescence detector will be comprehended between angles near the horizontal ($\sim 2^o$) and 30°, and a radius r of approximately 30 km. The maximal height from where the DB can be triggered by the fluorescence detector is h and ω is its projection in the DB propagation axis. The zenith angle is represented by θ.

We considered only showers moving away from the detector since, in the opposite case, a large amount of Čerenkov light arrives together with the fluorescence light, spoiling a precise data analysis [20].
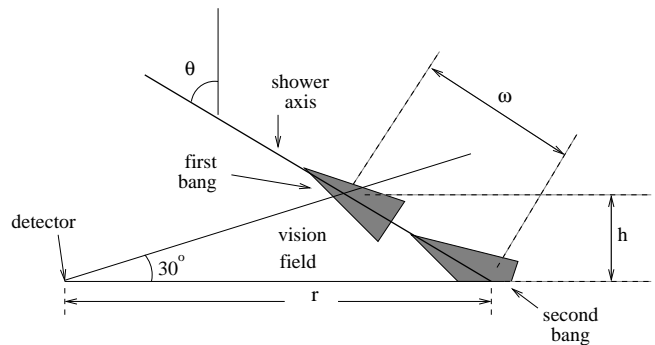

FIG. 1: A schematic view of a Double-Bang and the f.o.v. of the Pierre Auger Fluorescence Detector. See text for details.

The total amount of light emitted by the first cascade is related to the energy transfered to the quark at the moment of the first tau-neutrino interaction, which we will define as E_1. The neutrino energy E_ν is the sum of the tau energy E_τ and E_1, i. e., $E_\nu = E_1 + E_\tau$. For charged current interactions above 0.1 EeV, approximately 20% of the neutrino energy is transfered to the quark [21]. The second cascade, resulting from the tau decay, carries an energy E_2 of approximately $2/3\ E_\tau$ and is visible when the tau decay is hadronic, which happens with a branching ratio of around 64% [22].

Therefore, very roughly, we have $\langle E_1 \rangle \sim 1/5 E_\nu$ and $\langle E_2 \rangle \sim 2/3 \langle E_\tau \rangle \approx 8/15 E_\nu$ and the relation between E_1 and E_2 is given by: $E_2/E_1 = \frac{8}{15}E_\nu/\frac{1}{5}E_\nu \approx 2.67$. The distance traveled by the tau before decaying in laboratory frame is $L = \gamma ct$, where $\gamma = E_\tau/m_\tau$ and t is the mean life time of the tau, that has an error of approximately 0.4% [22].

A. Simulations

In order to infer the possibility of observing DB events in atmosphere and detecting them in the Pierre Auger Fluorescence Detector, we first simulate the longitudinal development of the showers. For simplicity, we numerically simulate DB events using protons as primary particles. We create two separated showers using the relations of energy (E_2/E_1) and distance (L) between the two EAS of a DB in the way presented in the previous section. In fact, it has been argued that it is difficult to distinguish if a ultra-high energy EAS was created by a proton or a neutrino [23, 24], at least when the cross section is extrapolated from the Standard Model. An important difference is the probability of interaction in the atmosphere, that can be 10^{-5} smaller for a vertical neutrino than for a proton. There are also some works that study the differences between the longitudinal development of EAS generated by protons, heavier nuclei and different neutrino flavors [24, 25]. In reference [25] they use CORSIKA+Herwig Monte Carlo simulations to have electron and muon-neutrinos as primary particles,

TABLE I: Parameters used in the numerical simulations with the CORSIKA program and primary neutrino energy of 0.5 EeV. For a visualization of the geometrical parameters θ, h and ω, see Fig. 1. The units are km except where it is pointed.

θ^a	1st. int.^{b}	$L\cos\theta^c$	2nd. int.^{d}	h^e	h (g/cm^2)^f	ω^g
45°	24.3	14.3	10	11	231	15.6
55°	19.6	11.6	8	9.5	291	16.6
65°	15.5	8.5	7	7.7	377	18.2
75°	10.2	5.2	5	5.5	515	21.3

^{a}Zenith angle measuring the shower incident axis inclination
^{b}Altitude of the first interaction in the atmosphere
^{c}Projection in the vertical axis of the distance the tau runs before it decays
^{d}Altitude where the tau decays
^{e}Maximum altitude from where the fluorescence light of the DB can be detected, for $r = 30$ km (see Fig. 1)
^{f}Same as h, but in units of g/cm^2, also called atmospheric depth
^{g}Projection of h in the DB propagation axis

TABLE II: Same as Table I, where the primary neutrino energy is taken to be 1 EeV.

θ	1st. int.	$L\cos\theta$	2nd. int.	h	h (g/cm^2)	ω
45°	33.6	28.6	5	11	231	15.6
55°	28.2	23.2	5	9.5	291	16.6
65°	22.1	17.1	5	7.7	377	18.2
75°	13.5	10.5	3	5.5	515	21.3

but not tau-neutrinos. So the simulations we have made to study DB events still are a good approximation. We discuss how to distinguish events that could masquerade tau-neutrino induced DB events in the conclusions.

Two different approaches can be taken to evaluate the longitudinal development of a DB. At first we used Gaisser-Hillas parameterization [26]. This method, nevertheless is not reliable to determine the depth of the shower maximum and the point of first interaction, specially for arrival angles larger than 60°. At this point, the CORSIKA simulation seems to be a good approach [27]. Here we use its version 6.00.

Fig. 2 and Fig. 3 present the main results of the simulations with the CORSIKA program. They show the longitudinal development of the DB for different incident angles chosen among the simulated events. Table I and Table II show the parameters used in the simulations. In these tables, the points of first and second interactions are chosen fixed parameters. The distance between the first and second interactions, as we pointed out above, is in accordance with the tau mean decay length (L) in the laboratory frame. Because of the small cross section of the neutrino, the probability of interaction in the top of the atmosphere is about the same for any point.

B. The number of events

To calculate the possible number of events in the Pierre Auger Fluorescence Detector, first consider for simplicity one detector with a site seeing of 360°. Then we can write the equation:

$$N_{events} = \int P_{det}(E, r, \theta, \varphi)\, \Phi_\nu(E)\, dE\, dA\, dT\, d\Omega \quad (1)$$

where,

$$P_{det}(E, r, \theta, \varphi) = P_{int}(E, \theta) \times P_{trig}(E, r, \theta, \varphi) \quad (2)$$

is the probability of detection of a DB in the Auger Observatory, given by the product of the probability $P_{int}(E, \theta)$ of the tau-neutrino to interact in the atmosphere and the probability $P_{trig}(E, r, \theta, \varphi)$ of the DB to be triggered by the fluorescence detector. $\Phi_\nu(E)$ is the flux of high-energy neutrinos depending on the model of the extragalactic source of high-energy cosmic rays. E, A, T and Ω are the energy of the incident neutrino, area over the f.o.v. of the detector, time of data acquisition and solid angle around the detector, respectively.

The interaction probability is given approximately by:

$$P_{int}(E, \theta) = \langle \sigma_{\nu N}(E) \rangle \times \langle N_T(\chi) \rangle \quad (3)$$

where $\langle \sigma_{\nu N}(E) \rangle$ is the average cross section of the neutrino-nucleon interaction and $\langle N_T(\chi) \rangle$, the average total number of nucleons per squared centimeter at the interaction point in the atmosphere. $N_T(\chi) = 2N_A\chi(\theta)$, where N_A is the Avogadro's number and $\chi(\theta)$ is the atmospheric slant depth at the neutrino-nucleon interaction point.

Considering the Earth's curvature, the slant depth can be approximately written as:

$$\chi(\theta) = \int_\lambda \rho\left(H = l\cos\theta + \frac{(l\sin\theta)^2}{2R}\right)d\lambda \quad (4)$$

where λ is the path along the arrival direction from infinity until the interaction point in the atmosphere, ρ is the atmospheric density, H the vertical height, l is the distance between the interaction point and the point toward the particle goes through on Earth (the slant height), and θ, the zenith angle. The atmospheric depth as a function of the zenith angle is shown in Fig. 4.

As the cross section of neutrinos with ultra-high energies is unknown, usually one adopts the extrapolation of parton distribution functions and Standard Model parameters far beyond the reach of experimental data. In this way, one can estimate a value for the cross section of the neutrino-nucleon interaction of about 10^{-32} cm^2, for energies around 1 EeV. Some authors say that this extrapolation gives a neutrino-nucleon cross section that is too high [28] but others use models that increase this same cross section to typical hadronic cross section values [24]. In this work we use the extrapolation of the Standard Model cross section.
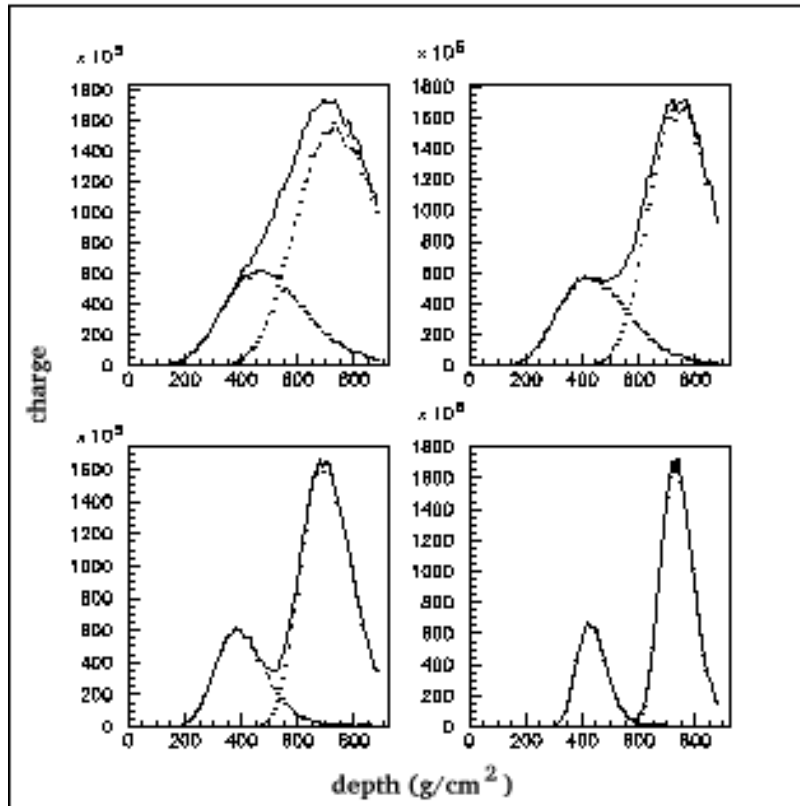
FIG. 2: Number of charged particles as a function of atmospheric depth in g/cm^2 simulated for incident angles of 45°, 55°, 65° and 75° from left to right and up to down. Inferior lines represent the first and second EAS, and the upper line is the sum when the two EAS are superimposed. The energy of the primary neutrino is 0.5 EeV.

The trigger probability is given by:

$$P_{trig}(E,r,\theta,\varphi) = \Upsilon \times P_{had} \times P_{db}(E,r,\theta,\varphi) \times \Sigma(E,r) \quad (5)$$

where Υ is the fraction of the time the fluorescence detector will work ($\Upsilon = 0.1$ because the fluorescence detector can only operate in clear moonless nights), P_{had} is the hadronic branching ratio of tau decay ($P_{had} = 0.64$), $P_{db}(E,r,\theta,\varphi)$ is the probability of the DB to be seen by the detector and $\Sigma(E,r)$ is the efficiency of the detector.

We define the probability of the DB to be seen by the fluorescence detector as:

$$P_{db}(E,r,\theta,\varphi) = \frac{\omega(r,\theta,\varphi)}{L(E)}, \text{ if } \omega(r,\theta,\varphi) \leq L(E)$$
$$= 1, \text{ otherwise} \quad (6)$$

where, as we have seen in Section II, $L(E)$ is the distance traveled by the tau in laboratory frame and $\omega(r,\theta,\varphi)$, as can be seen in the Fig. 1, is the size of the shower axis inside the f.o.v. of the detector. We made a rough approximation to account only for the showers moving away from the detector, so that $\int \omega(r,\theta,\varphi)d\varphi \sim \pi\omega(r,\theta)$. Then we measure $\omega(r,\theta)$ where the vertical plane containing the shower axis passes through the center of the fluorescence detector.

The efficiency $\Sigma(E,r)$ is the convolution of the energy efficiency $\Sigma'(E)$ and the efficiency depending on distance

$\Sigma''(r)$. As the fluorescence detector has no measurement of $\Sigma'(E)$ yet, but only expectations based on simulations, we constructed one function based on simulations that grows logarithmically from 0 to 1 in the interval of neutrino incident energy $0.3 < E$ (EeV) < 88 [29]. $\Sigma'(E) = 0$ if the energy is lower than the energies in this range and $\Sigma'(E) = 1$ if the energy is higher than that. $\Sigma''(r)$ is a Gaussian distribution centered at the point 15 km far from the detector, but for simplicity in the calculation we used a step function 20 km long centered at the same point. It does not make a great difference in the final result.

III. RESULTS AND DISCUSSION

Because the Auger Observatory Fluorescence Detector will be constituted of four detectors with a site seeing of 180°, we have to multiply the result of Eq. 1 by 2. Then using Eq. 1 we calculated the number of events which can be seen in Tables III and IV for different models of ultra-high energy cosmic ray flux and in different energy intervals.

From Table III one can learn which is the energy interval which is relevant to detect DB events in the Auger fluorescence detector. It is, approximately, $0.63 <$
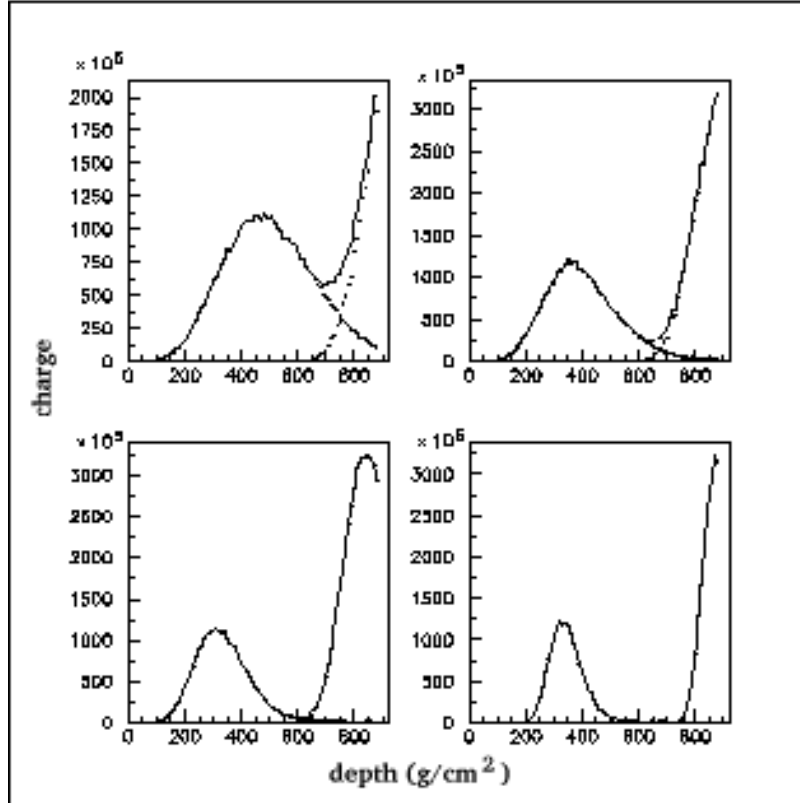
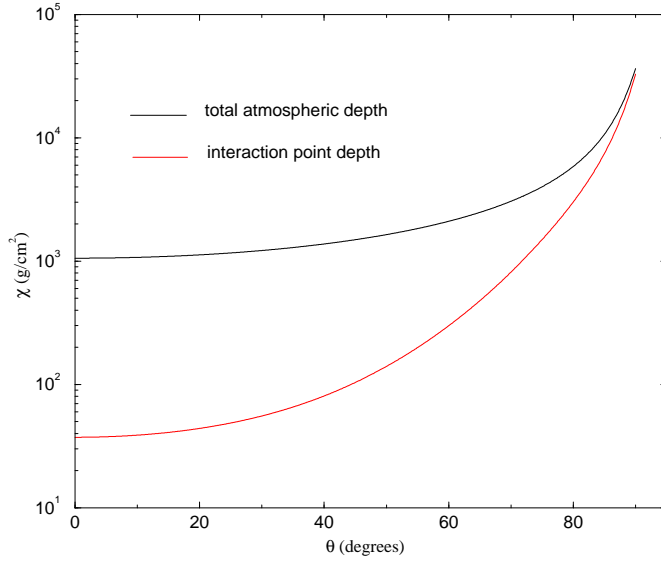FIG. 3: Same as Fig. 2, but the energy of the primary neutrino is assumed 1 EeV.

FIG. 4: Atmospheric depth as a function of the zenith angle. The inferior line represents the interaction point depth for $l = 30$ km.

TABLE III: Number of events in the fluorescence detector during a period of three years, calculated in different regions of the energy spectrum and for different models of neutrino flux. TD-92 stands for the model in reference [30]; TD-96 for the reference [31]; AGN-95J for [32]; WB for [33] and MPR for [34].

Models (p)	$N_1{}^a$	$N_2{}^b$	$N_3{}^c$	$N_4{}^d$
TD-92 (0)	260	450	180	70
TD-92 (0.5)	2.8	5.7	2.8	1.5
MPR	2.4	3.6	1.1	0.3
TD-92 (1)	0.14	0.37	0.25	0.2
AGN - 95J	0.15	0.22	0.07	0.02
TD-92 (1.5)	0.06	0.15	0.1	0.08
WB	0.05	0.08	0.02	0.01
TD-96 (1)	2.9×10^{-5}	3.1×10^{-5}	6.1×10^{-6}	1.0×10^{-6}

$^a 0.20 < E(\text{EeV}) < 0.63$
$^b 0.63 < E(\text{EeV}) < 2.00$
$^c 2.00 < E(\text{EeV}) < 6.30$
$^d 6.30 < E(\text{EeV}) < 200$

E (EeV) < 2. The neutrino flux used here for the model AGN-95J is an approximation that takes roughly the average between the models A and B in reference [32]. Table IV shows the expected number of DB events in three years according to the ultra-high energy cosmic rays source models, when a Standard Model extrapolation for the $\sigma_{\nu N}$ is used.

Based on the simulations shown in Section II A, one can have an idea of the longitudinal development of the

TABLE IV: Tau neutrino fluxes at the Earth according to the corresponding total number of events in a period of three years.

Models (p)	Φ_ν (GeV^{-1}m^{-2}s^{-1}sr^{-1})	N_{events}(3yrs)$^{-1}$
TD-92 (0)	$2.31 \times 10^{-2}E^{-1.77}$	9.6×10^2
TD-92 (0.5)	$5.64 \times 10^{-6}E^{-1.58}$	1.3×10^1
MPR	$2.15 \times 10^{-2}E^{-2}$	7.4×10^0
TD-92 (1)	$1.07 \times 10^{-9}E^{-1.3}$	9.6×10^{-1}
AGN - 95J	$1.34 \times 10^{-3}E^{-2}$	4.6×10^{-1}
TD-92 (1.5)	$4.24 \times 10^{-10}E^{-1.3}$	3.8×10^{-1}
WB	$4.83 \times 10^{-4}E^{-2}$	1.7×10^{-1}
TD-96 (1)	$7.51 \times 10^{-4}E^{-2.4}$	6.7×10^{-5}

DB as a function of the incident angle and energy of the primary neutrino. It is the convolution of the terms $P_{db}(E,r,\theta,\varphi)$ and $\Sigma(E,r)$ in Eq. 5 that describes the restriction in the energy interval observed in the simulations and Table III. For relatively low energies the efficiency $\Sigma(E,r)$ of the detector is also low and, as can be seen in Eq. 6, for energies higher than 2 EeV the factor $P_{db}(E,r,\theta,\varphi)$ is too small.

There is also a restriction for the neutrino incident zenith angle. For zenith angles smaller than 55°, because the lower atmospheric density, the development of the shower is slower and there is a superposition of the two EAS. The DB still can be triggered but in a more sophisticated way by comparing the longitudinal development of the EAS. Fig. 5 shows events with incident angles equal to 45°. In the simulations on the top of Fig. 5 we can observe the two overlapped showers such that they look like a single ordinary EAS. Even in that case one can see that it is possible to identify a DB because both the maximum of the charged particles number and the longitudinal development of the shower are not compatible with a "single-bang" of the same energy, which is shown in the lowest plot of Fig. 5. For zenith angles larger then 75°, since h (see Fig. 1) is too low, it is difficult to detect the first EAS.

We simulated sixty DB events for each different energy and angle that we present. The results have a root mean square deviation for the maximum of the showers of approximately 30 g/cm^2. As the maximum of the DB (top and central plots) in Fig. 5 is around 700 g/cm^2 and the maximum of the ordinary EAS (lowest plot) is around 500 g/cm^2, it is easy to differentiate between the depth of the maximum of a DB and an ordinary EAS in the simulations we made. If a higher energy proton will masquerade a lower energy DB depends on the accuracy of the detector to determine the energy of the primary particle. Because of the mean life time of the tau, only relatively low energy DB will be superimposed looking like an ordinary EAS. So if you detect an ordinary EAS profile of relatively high energy ($E > 10$ EeV), that cannot be considered a DB event.

To study the relation between the cross section and the potential of the Pierre Auger Fluorescence Detector to detect DB events we wrote the neutrino cross section as $\sigma_{\nu N} = A \times \sigma_{SM}$, where A is a free parameter which depends on the model and $\sigma_{SM} \sim 7.8\times10^{-36}$ cm$^2\times E^{0.363}$ is the Standard Model extrapolation for $\sigma_{\nu N}$ which have 10% accuracy within the energy range $10^{-2} < E(\text{EeV}) < 10^3$ when compared with the results of the CTEQ4-DIS parton distributions [35].

To account for models that gives a cross section different from the extrapolation of the Standard Model cross section we just vary A. It is a naive approximation but gives an idea of how the number of events can increase or decrease if the cross section is not standard. For instance, if the cross section is of order 10 times higher then the standard in the energy range $0.20 < E(\text{EeV}) < 200$, then even the WB upper bound for the ultra-high energy cosmic ray flux predict a rate of more than 1 event in 3 years in the Pierre Auger Fluorescence Detector.

The horizontal lines in Fig. 6 are number of events chosen for comparison (1 event in 3 years is considered the lower limit for the rate of events in the Auger Observatory). The vertical line shows the extrapolated Standard Model cross section. The other lines show the number of events for different models of ultra-high energy cosmic ray flux depending on A. For instance, we can see from this figure that assuming the Standard Model extrapolated cross section, if the Observatory measure a number of events around one in three years, models like TD-96(1), TD-92(0) and TD-92(0.5) will be excluded, and the more compatible with the measurements will be TD-92(1).

IV. CONCLUSION

Taken into consideration neutrino oscillations, one expect that one third of the high-energy neutrino flux arriving at the Earth should be composed of tau neutrinos. These neutrinos can interact in the Earth's atmosphere generating a double shower event named Double-Bang Phenomenon. Many recent works have studied the potential of the Pierre Auger Observatory to detect horizontal air showers generated by ultra-high energy neutrinos with the surface detector. Here we specifically investigate the potential of the fluorescence detector of that observatory to observe DB events.

DB events have very particular characteristics in the Auger Observatory. Different from the neutrino events in the surface detector, DB events do not need to come from the very near-horizontal angles. Despite the low probability of interaction in the atmosphere, we can also have tau neutrinos creating DB events with incident angles from approximately 55° to 75°. DB events also have a lower energy, around 1 EeV, different from the energies around 50 EeV and beyond expected for an ordinary EAS generated by the highest energy cosmic rays. In the range of energy approximately between 0.6 EeV and 2 EeV a considerable part of the two EAS that characterize a DB can be detected by the fluorescence detector
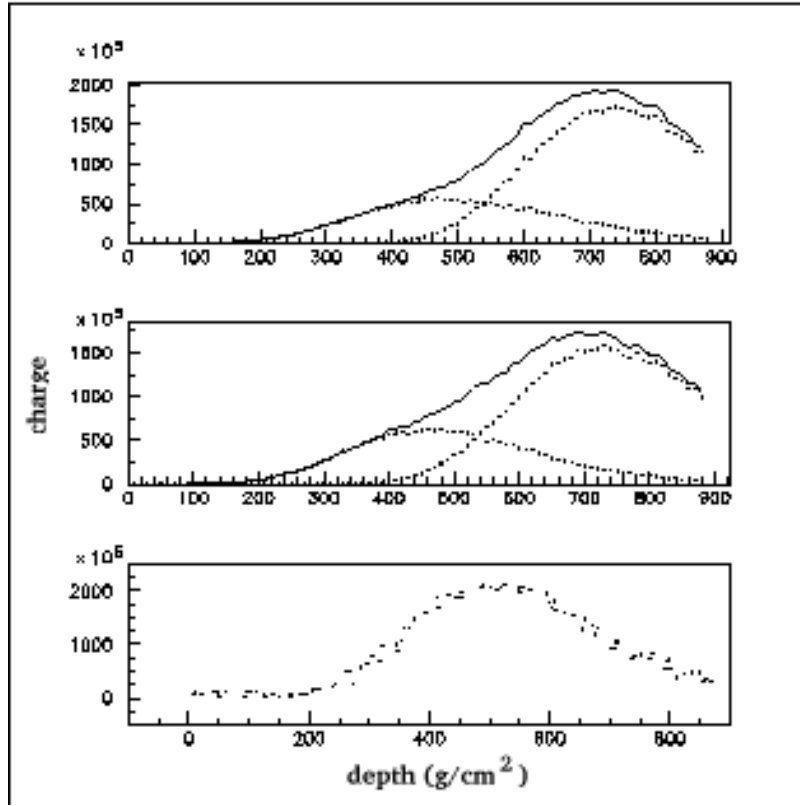
FIG. 5: Number of charged particles as a function of atmospheric depth in g/cm^2 simulated for an incident angle of 45° and depth of the first interaction equal to 24.3km $\approx$ 30g/cm^2. The first two graphics from the top were simulated using the CORSIKA program versions 5.62 (which is valid for zenith angles smaller than 60°) and 6.00 (which is valid even for zenith angles larger than 60°) respectively, with the energy summed of the two EAS equal to 0.5 EeV. Inferior lines represent the first and second EAS, and the upper line is the sum when the two EAS are superimposed. The graphic in the bottom is an ordinary shower simulated with the CORSIKA version 6.00 and energy of 0.5 EeV.
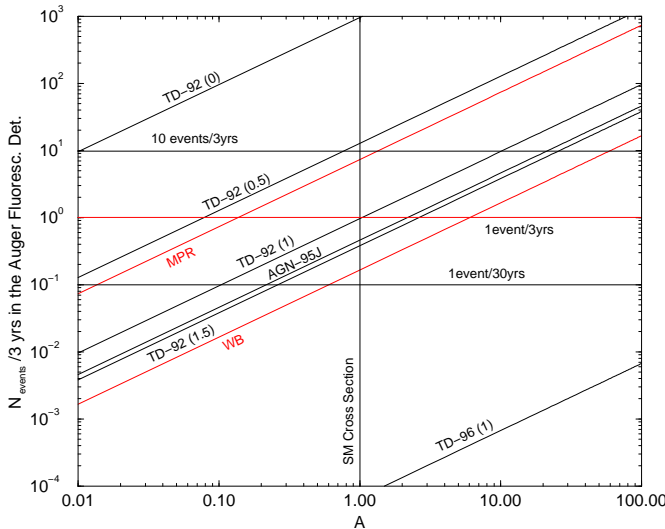

FIG. 6: Number of events according to the parameter A of the cross section for various models. $A = 1.00$ corresponds to the extrapolation of the Standard Model cross section. See text for details.

and then we have a DB trigger.

The number of DB events depends on many parameters like arrival flux, cross section, energy and incident direction of the neutrinos, and efficiency of the detector. Models like MPR, TD-92(1) and AGN-95J generate a number of events of around one in three years in the Pierre Auger Fluorescence Detector. This is because the energy range where the DB can be detected is very strict. For energies less then 0.6 EeV the efficiency of the detector is too low and for energies greater then 2 EeV the two EAS are too separated.

Concerning the background, the probability for a proton to generate a DB and masquerade the DB generated by a neutrino depends on two possibilities: 1) that the primary proton interaction generates some fragment that will give rise to a secondary shower deep in the atmosphere with energy higher then the first. 2) that another shower created by some independent particle interacts deep in the atmosphere masquerading the second EAS of the DB.

In the possibility 1, the second EAS will be created by the decay or interaction of the fragment deep in the atmosphere. We consider that the primary proton looses

roughly half of its energy to the secondary particles that constitute the EAS, and so it is very hard that the second EAS has more energy than the first one. Now, considering that for this high-energies we have a cosmic ray flux of the order of 1 particle per km^2 per year and that the only particles that could interact deeply in the atmosphere are neutrinos, generating the second independent EAS near the detector, the chance that the proton and this second independent neutrino come from the same solid angle direction interacting in a time interval of the tau decay in the laboratory frame of $\gamma t \approx 131 \times \frac{E_\nu}{[\text{EeV}]}$ μs is approximately (at most) 1 in 10^8, what exclude the possibility 2. The direction of the two EAS can be identified specially if two fluorescence detectors trigger the same DB event (with only one detector, it must be difficult to know the direction of the EAS in the plane that contains the EAS and the detector).

Based on this assumptions, E_2/E_1 can be a good parameter to identify DB events if the error and the average in the energy measure is within certain specific value. The error in the energy measured by the fluorescence detector will depend mainly on the atmospheric conditions but hardly will exceed 50%. For a DB event the situation is optimistic because the most important is the relation between the energies of the two EAS and this error is smaller than the error of the absolute energy of an ordinary EAS. We can make a conservative estimation of the error in the average ratio E_2/E_1 considering the error in the absolute energy of 50%. This will give a relative error to the energy ratio of 70%. So, since $E_2/E_1 \approx 2.67$ in

average as deduced in Section II, then considering such an error we find 95% of the events such that the energy ratio $E_2/E_1 > 1$. Then $E_2/E_1 > 1$ is a good parameter to identify DB events.

Despite the fact the DB Phenomenon can be very rare, it is very important to be prepared for its detection, specially in case the Pierre Auger ground array detect near-horizontal air showers which can indicate a sign for electron and/or muon neutrinos. Consequently oscillations imply a considerable number of tau neutrinos too. With such a motivation, the Auger Observatory could calibrate its trigger to be more sensitive to energies around 1 EeV or increase the number of fluorescence detectors.

The potential of the DB Phenomenon to acquire valuable information both in particle and astrophysics is irrefutable. For instance, the cross section and flux of the ultra-high energy neutrinos are speculative and can be investigated with DB events.

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